Project Final Report

I. Report Title, Author, Organization, Grant Number, Date

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Engineering Design and Analysis for More Secure Salmon Net Pen Systems

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II. Abstract

The purpose of this project is to promote the Maine salmon aquaculture industry by applying state of the art engineering tools to develop more secure net pens and mooring systems. The goal is to reduce farmed fish escapement and to open up more exposed areas necessary for industry growth. The approach involves deploying instrumentation to measure the environmental forcing characteristics and to mooring system loads. Current velocity data sets, considering flow reduction, are then used as input to a fluid-structure interaction computer model of the net pen and mooring system. Computer model simulations are performed to calculate the distribution of mooring system loads. These results are compared with data sets obtained from load cells deployed at the site to validate the numerical approach. The resulting loads of these simulations are then used with a structural finite element model of the net pen flotation pipe, made of High Density Polyethylene, to determine yield strength characteristics. Using the validated models for mooring system design and net pen structure analysis, the techniques were applied to an exposed site off the coast of Maine. Site conditions were determined a preliminary specification of components were made.

III. Executive Summary

To evaluate mooring system and net pen structural components of a near shore fish farm, computer model techniques were developed and validated using field measurements. Developing these engineering methods will help to reduce farmed fish escapement and may open up more exposed areas necessary for industry growth. The study centered on a fish farm located in Broad Cove near Eastport Maine, USA, which is connected to the Bay of Fundy. The farm consists of 20 net pens connected to a near-surface mooring grid with 26 anchor legs. The net pens are constructed from circular pipe made of High Density Polyethylene with a circumference of 100 meters. The net pen and mooring gear components at the southwest portion of the farm was the primary focus in this study since the incoming tides come from this direction.

A field measurement program was conducted at that location where specific current meter data sets were obtained and used as input to a mooring system design model. Field measurements also included anchor leg and net pen attachment line tensions acquired using load cells. Current meters and load cells were deployed around the southwest net pen during three operational conditions, with (1) clean containment and predator nets for smolts, (2) clean containment and predator nets for standard grow out and (3) containment and predator nets for standard grow out at the end of the stocking schedule (approximately 16-18 months). At the end of the stocking schedule, the gear is typically fully fouled with biological material. Using the mooring system model with the current velocities as input, simulations were performed with and without current velocity reduction for clean and fouled nets and the results compared with the load cell measurements.

The next step was to develop a Finite Element Modeling (FEM) procedure to evaluate the structural capabilities of HDPE pipe. This was done by utilizing shell elements, and employing localized failure criterion. One of the primary inputs to the FEM is the material modulus of elasticity (E), which was determined by conducting a series of laboratory tensile tests using a range of loading rates. Once an estimation of E was obtained, a set of tests was conducted to investigate the failure of simple circular rings of pipe. Five circular samples of actual pipe were tested to localized failure in the laboratory. The laboratory tests were replicated using FEM simulations. The results were then compared and validated. The FEM approach was applied to the more complex geometry of the pen flotation structure to examine the maximum stresses in the pipe during operation at the farm and to investigate the maximum load the net pen pipe assemblies can handle.

The modeling techniques, developed to calculate mooring tension and net pen structure stresses, were used to investigate potential designs for more exposed offshore sites. The site was specifically chosen to have strong currents and large waves. It is located southwest of the Grand Manan Channel off the coast of Maine. Maximum tidal current velocities were obtained from the National Oceanic and Atmospheric Administration data sets. Wave conditions for the 10-, 25- and 50-year return periods where calculated from hindcast simulations performed by the United States Army Corps of Engineers and high-resolution wave conditions were obtained using the numerical wave model SWAN. Using these combined data sets, design wave and current conditions were obtained and used with a JONSWAP spectrum (fitted for the site) as input to the mooring system numerical model. Anchor leg and net pen attachment (Y-line) tensions were calculated. The tension values were used to specify components. The net pen attachment loads were used with the structural model to investigate potential HDPE pipe sizes.

IV. Purpose

The objective of this project was to analyze a large near shore fish farm located at a site in Broad Cove (Eastport Maine, USA) to evaluate the structural integrity of the deployed system. The research is performed in an effort to minimize escapement and for offshore application. Engineering methods and tools were developed and applied. The procedure includes the analysis of the mooring system and net pen structures using computer models validated with field measurements. The models were then used to provide mooring and net pen stress analysis to minimize the escapement of the contained salmon in an offshore application. The specific goals were to:

1. Evaluate the historical record of wear and gear failure at the Broad Cove farm to identify known problem areas.
2. Deploy instrumentation to measure wave and current activity as well as the corresponding forces in mooring lines and critical cage components.
3. Use the environmental forcing data as input the University of New Hampshire numerical model to predict internal loads acting on mooring gear and cage structures.
4. Validate the numerical model for large salmon net pen systems by comparing model predicted forces with field measurements.
5. Apply a structural FE model to evaluate cage structural integrity.
6. Use the experience gained to evaluate the standard cage/mooring grid system (using the combination of aquaculture system structure models) for use at a more exposed sites.

The objectives focus upon the Federal Register/Vol 67, No. 93 Funding Priority A: Atlantic Salmon Aquaculture Development Considering the Endangered Species Status of Atlantic Salmon. The approach specifically targets the program area to establish more secure cages to reduce farmed fish escapement. In addition to this objective, the work investigates the feasibility of expanding fish farming operations into more exposed areas in an effort to reduce environmental and multi-use issues that occur at many near shore sites.

V. Approach

A. Overview

The approach taken to complete this extensive project has been organized into multiple page chapters found in the attached detailed report. An overview of each chapter is provided below along with the individuals and organizations that performed the work.

B. Chapter 1: Introduction

The Introduction chapter describes in detail the characteristics of the fish farm site, net pen structure and mooring system specifications. This chapter also expands on the specific objectives and provides an overview of the general approach. The principal investigator of the project, Dr. David W. Fredriksson (USNA), was the primary author.

C. Chapters 2 and 3: Field study to understand the currents and loads

An extensive field study was conducted to investigate the current velocity loading and mooring system tension in the 20-unit net pen fish farm. Since the farm is located in Eastport Maine, USA near the Bay of Fundy, extreme tides create strong currents that create the primary forcing on the system. Current meters were deployed at external and internal locations of the farm during three distinct operational conditions. The conditions considered are for a farm with (1) clean nets for smolts, (2) clean nets for standard grow out and (3) nets for standard grow out at the end of the stocking schedule. At the end of the stocking schedule, the gear is typically fully fouled with biological material.

During these conditions, a Nortek AQUADOPP current meter was installed on the outside of the farm to measure the forcing velocities, which generally are the largest from the South and West. A second current meter, a Nobska MAVS, was deployed at the site behind the SW net pen. Additional current meters were also deployed at the site. During the smolt net installation, an InterOcean S4 was deployed between the two net pens on the NE corner of the farm to obtain a "far field" measurement of flow blockage. During the fouled net installation, an ADCP was placed outside of the mooring grid. In addition to the current meters, the field program included deployment of nine load cells and recorders around the same net pen and mooring components in the southwest corner to measure forces in the anchor legs and the net pen attachment lines. Five load cells were shackled into the mooring chain on the five anchor legs on the west and south sides of the focus area. Four load cells were placed in the attachment from the two south corners of the focus area that hold the net pen in the mooring grid. The current meters and load cells recorded data during the three different net size and fouling conditions. The results of the load cell measurements were used with the current meter data sets to gain insight between the relationship of the forcing of the tidal currents, tension in the mooring gear components and the amount of flow blockage by the different net configurations.

The results provide evidence of significant velocity reduction through the farm. The highest current velocity reduction occurred during the fouled net condition. The highest tension measurements, however, were found during the clean net condition with maximum tensions observed in the west anchor line of approximately 104 kN (23,000 lbf). The SW net pen attachment lines, however, had maximum tensions of around 3,000 lbs, much less than the anchor lines in mooring grid holding 20 net pens. The flow and tension data sets were used to quantify flow reduction characteristics (Chapter 4), to validate Morison equation type numerical models (Chapter 6) and with net pen structural models (Chapter 7). These techniques can then be used in site studies and to aid in the design of and for specifying offshore fish farm gear.

The work described in these chapters was performed under the direction of Dr. David W. Fredriksson (USNA). He worked with Mr. Judson DeCew (UNH), and with Dr. James D. Irish (WHOI) in the development of the field program, programming of instrumentation, deployment and recovery operations and processing of acquired data sets. The team was able to work with the operation crew at the Broad Cove fish farm site utilizing their vessels and expertise during the field program.

D. Chapter 4: Characterization of the velocity flow reduction through the farm

This portion of the study employs a combination of field measurements, analytical techniques and computational fluid dynamics to characterize the horizontal flow reduction through the floating multi-pen fish farm for the three operational conditions. As part of the field program, current meters were deployed at exterior and interior locations around the farm. Data sets obtained from the current meters were processed to obtain Root Mean Square velocity information. The velocity reduction information for each operational condition was utilized with the results of an analytical approach. The analytical technique estimated respective coefficient of drag values obtained by considering a balance between the time rate of change of kinetic energy and the work performed on the farm. The horizontal velocity reduction information is incorporated into a mooring system model to calculate mooring system drag loads. The calculated tensions are being compared with measurements from load cells deployed on the system.

The work performed as part of this chapter was supervised by Dr. David W. Fredriksson (USNA). Dr. Fredriksson and Mr. Judson DeCew processed data sets and interpreted in-situ, analytical, and CFD results. Dr. Patrick J. Hudson (APL-Johns Hopkins) performed the CFD simulations. Dr. M.R. Swift (UNH) assisted with the development of the analytical current reduction scheme.

E. Chapter 5: Development of Load Cases for the Mooring System and Net Pen Structural Modeling

The data set results described in Chapters 4 and 5 were analyzed for suitable current velocity and mooring tension combinations for model validation studies. Two numerical modeling techniques are being developed to (1) calculate mooring system tension (Chapter 6) and (2) determine stresses in net pen structural components (Chapter 7). The general guidelines for selecting data sets for mooring system modeling validation were such that both the current velocity and tension values were relatively steady. For the structural modeling, the direction of the current velocity had to be "in-line" with the Y-line net pen attachments. Multiple load case candidates were identified.

The data processing was performed by Mr. Judson DeCew and Dr. David W. Fredriksson.

F. Chapter 6: Comparison of in-situ mooring load measurements with the numerical model simulation.

This portion of the study was conducted to validate a numerical model of the large fish farm containing 20 net pens. The model is forced using measured current velocity values obtained outside of the farm. Mooring line tensions calculated with the numerical model are compared with load-cell field data sets. The approach considers velocity reduction and load characteristics that occur through the net pen system for both clean and fouled net conditions. Without reduction, the mooring system model produces excessively conservative results. With reduction, a substantial improvement occurs. The large fish farm validated model is used to design systems for exposed sites (Chapter 8).

The work in this chapter was supervised and written by Dr. David W. Fredriksson (USNA). The mooring system numerical model development and application was performed by Mr. Judson DeCew (UNH – Ocean Engineering). Dr. Igor Tsukrov (UNH – Mechanical Engineering) provided numerical method technical guidance and writing.

G. Chapter 7: Development of Structural Models for Evaluating HDPE Plastic Net Pens

A finite element methodology is developed to determine the structural capabilities of net pen flotation structures made of High Density Polyethylene (HDPE). The approach considers the use of shell elements and localized failure techniques. Since HDPE is a viscoelastic material, the modulus of elasticity needs to be determined as a function of loading rate. Values for the modulus of elasticity were determined by performing a series of tensile tests. To investigate the effectiveness of the approach, a series of experiments were performed in the laboratory by testing rings of HDPE pipe to localized failure ('kinking") and comparing the results with numerical model simulations. Measured and calculated results were within 16%. The combined technique was used for the complex geometry of a net pen flotation structure using experimentally determined material properties. Results of the numerical simulations show that this component of the net pen may fail at attachment loads approximately 53 kN.

The work performed in this chapter was supervised and written by Dr. David W. Fredriksson (USNA). Mr Judson DeCew (UNH) performed the structural modeling simulation under the guidance of Dr. Igor Tsukrov (UNH). Dr. Tsukrov also provided technical writing assistance.

H. Chapter 8: Conceptual Design of a Large Offshore Fish Farm

The first step in the design process was to understand the limits of the components used in the near shore system. Modeling techniques were developed to calculate mooring tension and net pen structure stresses. The next step was to use this knowledge to investigate potential designs for more exposed offshore sites. The site was specifically chosen to have strong currents and large waves. It is located southwest of the Grand Manan Channel off the coast of Maine. Maximum tidal current velocities were obtained from the National Oceanic and Atmospheric Administration group called CO-Ops (http://co-ops.nos.noaa.gov). Wave conditions for the 10-, 25- and 50-year return periods where calculated from hindcast simulations performed by the United States Army Corps of Engineers, Wave Information Study (http://wis.mil). Additional, high-resolution wave conditions were obtained using the numerical wave model SWAN. Using these combined data sets, design wave and current conditions were obtained. A current velocity of 2 m/s, a significant wave height of 7.2 meters with a dominant period of 9.7 seconds was used with a JONSWAP spectrum (fitted for the site) as input to the mooring system numerical model. Anchor leg and net pen attachment (Y-line) tensions were calculated. The tension values were used to specify components. The net pen attachment loads were used with the structural model to investigate potential HDPE pipe sizes.

This work was supervised and written by Dr. David W. Fredriksson (USNA). Dr. Fredriksson also developed the design environmental loading conditions. The modeling simulations were performed by Mr. Judson DeCew (UNH) and the wave simulation conducted by Dr. Doncheng Li and Dr. Vijay Panchang(Texas A&M-Galveston)

VI. Findings

A. Chapters 2 and 3

The current velocity measurements at each location were processed using basic statistics and for tidal harmonic constituents. For all three deployments, the maximum velocities outside the farm were approximately 0.76 m/s. Examining the basic statistics for each of the deployment locations showed evidence of velocity reduction through the farm (though for the clean net condition, the differences were small).

Next, using the raw current velocity data sets shown, tidal harmonic analysis was also performed. The tidal constituent amplitudes for the internal and external positions also showed evidence of velocity reduction. Taking the East- and North-going M2 tidal components and plotting them with respect to each other for each condition and location, provided additional evidence of velocity reduction. This may significantly affect the calculation of drag loads and therefore the specification of components. Further examination of this issue is described in Chapter 4.

The current meter measurements also yielded additional results. As expected, the M2 constituent was found to be the dominant tidal component. Actually, most circulation studies involving hydrodynamic models built for the region are forced using M_2 tidal characteristics. Results from the measurements taken as part of this study, however, showed evidence of shallow water overtide influence, which includes the superposition of the M_4 and M_6 constituents. The contribution of overtides is important in the accurate representation of velocities in estuaries that are relatively shallow with large tidal amplitudes. Evidence from this data set, showed that future hydrodynamic modeling studies of the area should consider overtide influence. This is important since 26 finfish lease sites are located in the area and the understanding of the transport of wastes and diseases may help guide the operation and management of the facilities since overlap may occur.

Under normal tidal current conditions, the maximum anchor loads "experienced" by the system approached 104 kN (23,000 lbf). These loads occurred on the west side of the system, which was consistent with information obtained from discussions with operational personnel that have had to reset gear at this location on multiple occasions. The components used on the western anchor legs consist of 1-1/2" long link steel chain with an approximate working load (new) of 150 kN (33,800 lbf) and two stockless anchors with a capacity of 60-80 kN each. So the primary mooring components were specified appropriately.

The Y-lines consist of 1 inch (24 mm) co-polymer (polypropylene and polyethylene fiber) in a three-strand construction with a manufacturer's average tensile strength of 97 kN (21,730 lbf). The load cells were deployed on the double end of the Y-line where it connected to the cage. The other (single) end of the Y-line connected to the daisy plate on the mooring system. By examination of individual data sets, the maximum loads occurred when one portion of the "Y" was taking up the load (the other end usually had much less load). The total load from one side of the Y is assumed to transfer directly to the mooring. Maximum load values measured were approximately 9.8 kN (2200 lbf). Comparing this value with the minimum breaking load (147 kN) from the manufacturer indicates that this component is also specified appropriately.

B. Chapter 4: Characterization of the velocity flow reduction through the farm

As previously described, a field data set of synoptic horizontal velocity measurements were obtained from the fish farm during the three distinct operational conditions. The conditions were characterized by the type of the nets installed and the amount of biological material on the nets. The data sets were synthesized to obtain the dominant RMS velocity components from which velocity reduction values through one net pen layer were calculated regardless of the physical conditions that occur during the tidal cycle. Since a limited number of instruments were available, the horizontal velocity reduction through multiple cages was estimated using an analytical approach assuming an ideal situation considering control volume concepts.

The analytical velocity reduction was tested using CFD techniques where clean predator and containments (condition #2) were modeled as a porous jump. A farm with 20 net pens was then created and subjected to a 0.20 m/s velocity and flow reduction estimated across a diagonal row of cages. At distinct horizontal locations, the CFD generated reduction results were compared well with those calculated from field-derived values with the analytical estimations. The percentage differences were within 10 points.

The goal of applying this approach is for accurately calculating tension in mooring components. Therefore, the validity of this method lies in the comparison of calculated mooring tension values with measured values from the load cell recorders also deployed as part of the field program. This portion of the study is described in Chapter 6.

C. Chapter 5: Development of Load Cases for the Mooring System and Net Pen Structural Modeling

The next step was to analyze the field data sets to identify potential load case candidate for the mooring system and structural modeling studies. Load cell data sets were required to validate the mooring system model for large near-shore fish farms under static, pre-tension conditions and under current velocity loading. The model is used to perform anchor leg tension calculations and the results compared with measured values. Information from conditions #2 and #3 were used for this purpose. Current velocity and load cell data sets were also collected for the structural modeling portion of the project. In these cases, the load cell values are used as input so that operational stresses in the flotation rim of the net pen can be calculated.

Based on the criteria presented in this Chapter and review of the candidate load cases, the selected load cases used for validation purposes are:

- 28-Jul-2004 at 2100 UTC – Clean Nets (Mooring System Model)
- 28-Oct-2003 at 0200 UTC – Fouled Net (Mooring System Model)
- 05-May-2004 at 1400 UTC – Smolt Nets (Structural Model)
- 16-May-2004 at 2200 UTC – Smolt Nets (Structural Model)

D. Chapter 6: Comparison of in-situ mooring load measurements with the numerical model simulations.

Enabling horizontal flow reduction to be simulated in the mooring system model provided insight to the tension distribution in the mooring lines of the fish farm. Without reduction, anchor leg tensions on the load bearing side of the farm were greater when reduction was employed. On the "slack" side of the farm, the opposite was true, since the higher velocities allowed more set back. Both sets of results indicated that for diagonal, on-coming currents, the critical anchors are at middle locations. The results also show that the grid components, in the ideal geometric case, effectively distribute loads throughout the farm.

The direct comparison between the field measurements and model simulation results can be difficult since many uncontrollable variables exists *in-situ*. One such set of variables includes the geometric properties of the 26-leg mooring grid. In the numerical model, each leg pre-tension characteristic is estimated using the ideal deployed configuration. During fish farm operations, high horsepower vessels are used to set the leg by throttle control. Therefore, it is unlikely that the actual farm is evenly pre-tensioned in the ideal configuration. Evidence of this exists by examining the load cell data sets obtained from the western anchor leg during the clean net deployment, where values appeared to be high. It was known from the field crew that this leg was stretched out considerably more than the other anchor legs. Nevertheless, when the measured data set values were compared to the calculated results, clear trends were evident. Employing the velocity reduction knowledge enables a better tension estimate, though not exact. This can have implications when specifying gear and safety factor using the model.

The mooring system model is an important tool in the design of fish farm structures. The new version of the model presented in this study can be used to calculate the distribution of mooring line loads in complex grid mooring systems. Critical components for design specification can be identified to prevent potential system failures. Failure can have dire consequences, especially in an industry where the profit margin can be small. In this context, over prediction of calculated tensions can lead to the specification of oversized equipment. Larger floats, rope, shackles, and chain sizes are more expensive. The larger components will also be more difficult to handle on a daily operational basis.

In addition, the mooring system model was modified to incorporate changes in the horizontal velocity as the flow passes through a multi-pen system. Without reduction, loads can be over predicted as shown by comparing model with the field results. Furthermore, the influence of the net condition (clean vs. fouled) will affect how much reduction is applied. Both conditions need to be considered in the design process. These results will become more important as the industry considers moving operations into more exposed or even open ocean conditions.

E. Chapter 7: Development of Structural Models for Evaluating HDPE Plastic Net Pens

It is clear from the field data sets (through normal operation) that the HDPE pipe used for this near-shore fish farming application is appropriate. The structural modeling techniques developed, however, enable the evaluation of acceptability margins. In the Broad Cove case, the estimated maximum Von Mises stress values were more than five times less than the yield stress. For the maximum load condition, it was necessary to consider the attachment configuration, where the worst-case situation would occur as a point load. Utilizing two sets of Y-lines (four attachment locations) minimizes the chance of this occurring.

The technique to structurally model HDPE pipe used in fish farm net pens show promise as an effective tool for specifying these components. As with many modeling applications, however, these results must be considered approximate. The failure criteria are subjective and the boundary conditions simplified. In addition, the question remains as to the appropriate loading rate, which affects the modulus of elasticity for visoelastic materials. Quantifying the load rate in environments with waves and currents may not be trivial. This will become more important if these structures are considered for more exposed or open ocean environments.

F. Chapter 8: Conceptual Design Considerations for an Offshore Farm

The knowledge gained from deploying the current meters and load cells, along with the modeling of the mooring system and net pen structure at the Broad Cove site provided the validated methods for designing fish farm structures. It is clear that the equipment specified for Broad Cove is appropriate since system failures typically do not occur. If the gear, however, is to be deployed at a more expose location, choosing sizes of rope, chain, shackles and HDPE pipe must be done in a quantifiable manner. As described in Chapter 8, an extreme site was chosen in the southwest portion of the Grand Manan Channel. Characteristic waves and currents were obtained and used to predict stresses in preliminary mooring components. Attachment line tension results were used as input to the structural model. Nearly all of the near shore components were not suitable. The next step would be to use the stresses in an iterative process. Following steps would include choosing more robust components, identifying the material and geometric properties, and use them as input to the mooring system model. Next, additional simulations performed and the entire process repeated until yield stress values are within a certain factor of safety (depending upon the component). Attachment line results from these simulations are then used with updated structural models to identify the appropriate pipe sizes for the net pen flotation structure. Utilizing these techniques and modeling tools will enable engineers to design fish farming systems to prevent escapement and component failure at new near shore sites and in higher energy environments.

Description of need for additional work

Even though an extensive amount of field data sets were acquired, lessons learned could warrant additional work. One of the most complicated issues to resolve in this project was characterizing the flow reduction through the farm. Additional synoptic measurements (more current meters) could have been deployed during the three operational conditions of net type and solidity. It may also have been useful to perform transects through the farm.

Applying Computational Fluid Dynamic techniques to understand the flow characteristics through the farm is another area worth investigating. The preliminary CFD results described in Chapter 4 provided insight regarding the velocity reduction through the farm (though not a part of the original proposed work). CFD methods validated with field measurements could be used not only for mooring system modeling of tension, but also for environmental purposes (e.g. oxygen exchange).

VII. Evaluation

A. Describe the extent to which the project goals and objectives were attained.

1. Were the goals and objectives attained?

As outlined in Section IV, there were six primary goals of this project. Each goal was accomplished. The critical components of the farm (i.e. focus area) were determined. Data sets from the field measurement program produced valuable information regarding the current velocities at the site and the tensions in the mooring components. It was found that the velocity reduction through the farm was dependent on the type and condition (e.g. biological fouling) of the nets. Numerical modeling techniques to calculate mooring system loads were developed considering the flow reduction characteristics. The results, when compared with field measurements, validated the approach (though not exact). The model can now be used with confidence, to specify mooring components (e.g. rope, chain, shackles) for large fish farm systems. Net pen structural components can also be compromised resulting in escaped fish. Sizing HDPE pipe for this purpose is not trivial and in the past has been determined typically by trial and error. Using the described FEM approach, models of HDPE net pens were created and critical stresses estimated. This model can also be used with confidence in the specification of HDPE pipe for net pen components. Using the developed modeling techniques, a case study was performed to estimate potential loads and stresses on potential offshore fish farm components. Initial results may seem extreme, but now the tools and techniques are available to optimize designs.

2. Were modifications made to the goals and objectives?

The current meter deployment scheme (part of the field program) was the most substantial modification to the approach. Originally, it was planned to move the current meters to several different locations over multiple deployments to measure reduction at different places in the farm. This assumed that the net conditions were relatively the same throughout the grow-out cycle. However, it was decided to take advantage of the different net types and conditions over the 18-month cycle to characterize these differences instead. The field deployment plan was also changed to accommodate availability of load cells. During the first deployment, leakage occurred with several of the instruments. These instruments were repaired and eventually deployed.

B. Dissemination of Project Results

The project results have been disseminated through three major venues:

- Conference and Workshop Presentations
- Peer Review Journal Publications (submitted)
- Complete Online Website maintained at the United States Naval Academy and Texas A&M Galveston (wave modeling)

Conference Presentations: The following conference presentations included material and research results obtained as part of this project.

Fisheries Dynamics (2003): *Open Ocean Fish Cage and Mooring System Modeling* presented by D.W. Fredriksson at the National Fisheries Research and Development Center in Busan, South Korea on September 24. Contributing authors: Igor Tsukrov, Ken Baldwin, Rob Swift and Barbaros Celikkol.

Pukong National University (2003): *Open Ocean Fish Cage and Mooring System Modeling* seminar presented at the Pukong National University in Busan, South Korea on September 25, 2003.

World Aquaculture Society Conference (2004): *A Study of the Structural Integrity of Salmon Net Pen Gear for Deployment in Exposed Locations*. March 2004 in Honolulu, Hawai'i, USA. Contributing authors: Jud DeCew, James Irish and Igor Tsukrov.

Aquaculture Association of Canada Conference (2004): *The Evaluation of Inshore Salmon Farm Mooring Technology for Use in More Exposed Locations* presented by D.W. Fredriksson. Contributing Authors, Jud DeCew, Igor Tsukrov, James D. Irish, and Vijay Panchang. October, 2004 in Quebec City, Canada.

Aquaculture Association of Canada Conference (2004): *Examining the Structural Integrity of Typical Inshore Salmon Farm Fish Cages for use in more Exposed Locations* presented by J.C. DeCew. Contributing Authors, D.W. Fredriksson and Igor Tsukrov. October, 2004 in Quebec City, Canada.

Aquaculture Association of Canada & Newfoundland Aquaculture Industry Association Conference (2005): *University of New Hampshire Engineering Activities relating to Open Ocean Aquaculture* presented by J.C. DeCew. Contributing Author, Michael Chambers

Open Ocean Aquaculture Engineering Workshop (2005). *Development of Structural Models for Evaluating HDPE Plastic Net Pens used in Marine Aquaculture* presented by D.W. Fredriksson at the University of the Faroe Islands. August 14, 2005. Contributing Authors: Judson Decew and Igor Tsukrov. See http://torshavn.no/index.php for workshop details.

Open Ocean Aquaculture Engineering Workshop (2006). *Development of Engineering Techniques for Designing an Offshore Fish Farm* by D.W. Fredriksson. August 2006 in Turkey.

Oceans/Marine Technology Society/IEEE Conference (2006). *A Field Study to Understand the Currents and loads of a near shore finfish farm* by D.W. Fredriksson. Contributing Authors: J.C. DeCew and J.D. Irish.

Peer Review Journal Publications: The following journal manuscripts are being prepared. Including in the listing for each paper is the title, authors and journal.

Fredriksson, D.W., Decew, J.C. and J.D. Irish (2006). A field study to understand the currents and loads of a near shore fish farm. To be submitted to the IEEE Journal of Oceanic Engineering.

Fredriksson, D.W., Hudson, P.J., Decew, J.C., Swift, M.R. and C. Stevens (2006). Characterization of the velocity flow reduction through a floating, multi-cage fish farm. To be submitted to Ocean Engineering.

Fredriksson, D.W., Decew, J.C., Tsukrov, I and J.D. Irish (2006). Comparison of in-situ mooring load measurements of a floating fish farm with numerical model simulations. submitted to Aquacultural Engineering.

Fredriksson, D.W., Decew, J.C. and I. Tsukrov (2006) Development of structural models for evaluating HDPE Plastic Net Pens used in Marine Aquaculture. To be submitted to Aquacultural Engineering.

Fredriksson, D.W. Decew, J.C. Li, D. and V. Panchang (2006). Design of an offshore fish farm: Application of mooring system, Cage Structural and Wave Prediction Models. To be submitted to Oceanic Engineering International.

Online Website: A website of the entire the entire project can be found on the USNA hosted site - http://cadigweb.ew.usna.edu/~fredriks/. The website includes details regarding (1) cage structural modeling, (2) mooring system modeling (3) field instrumentation and (4) wave modeling. The front page is shown below on Figure 1.

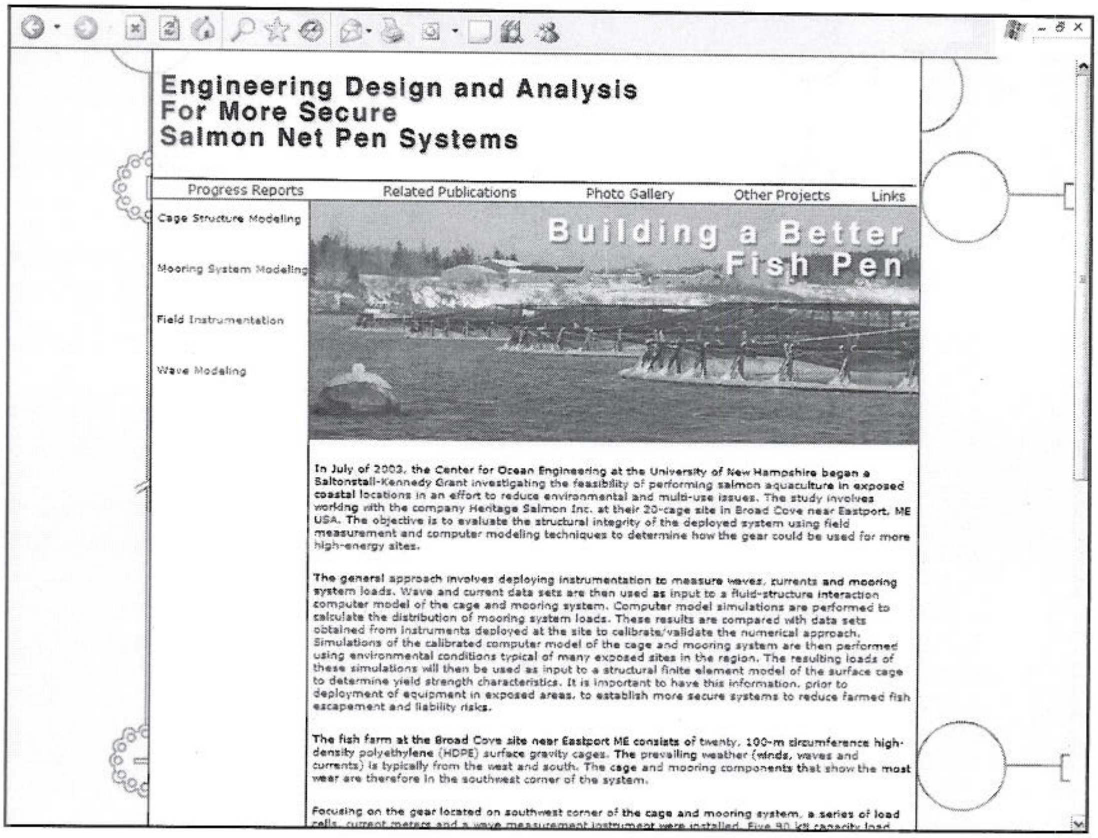
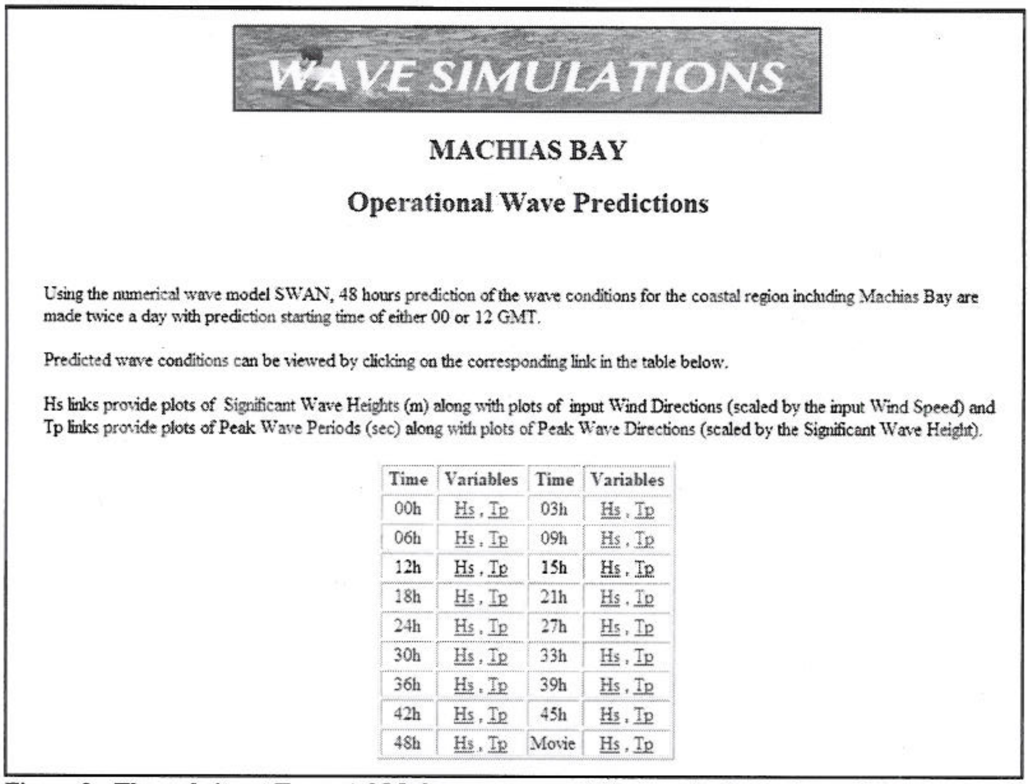


Figure 1: The project website is presently located at http://cadigweb.ew.usna.edu/~fredriks/.

In addition to the main project website, Texas A&M at Galveston also maintains a wave modeling website of the Gulf of Maine region partially funded by this project. It can be found at http://www.tamug.edu/mase/Wave_file/MACHIAS.htm. Figure 2 and 3 are examples from this website.



WAVE SIMULATIONS

MACHIAS BAY

Operational Wave Predictions

Using the numerical wave model SWAN, 48 hours prediction of the wave conditions for the coastal region including Machias Bay are made twice a day with prediction starting time of either 00 or 12 GMT.

Predicted wave conditions can be viewed by clicking on the corresponding link in the table below.

Hs links provide plots of Significant Wave Heights (m) along with plots of input Wind Directions (scaled by the input Wind Speed) and Tp links provide plots of Peak Wave Periods (sec) along with plots of Peak Wave Directions (scaled by the Significant Wave Height).

Time	Variables	Time	Variables
00h	Hs , Tp	03h	Hs , Tp
06h	Hs , Tp	09h	Hs , Tp
12h	Hs , Tp	15h	Hs , Tp
18h	Hs , Tp	21h	Hs , Tp
24h	Hs , Tp	27h	Hs , Tp
30h	Hs , Tp	33h	Hs , Tp
36h	Hs , Tp	39h	Hs , Tp
42h	Hs , Tp	45h	Hs , Tp
48h	Hs , Tp	Movie	Hs , Tp

Figure 2: The website at Texas A&M shows wave modeling results from the region.

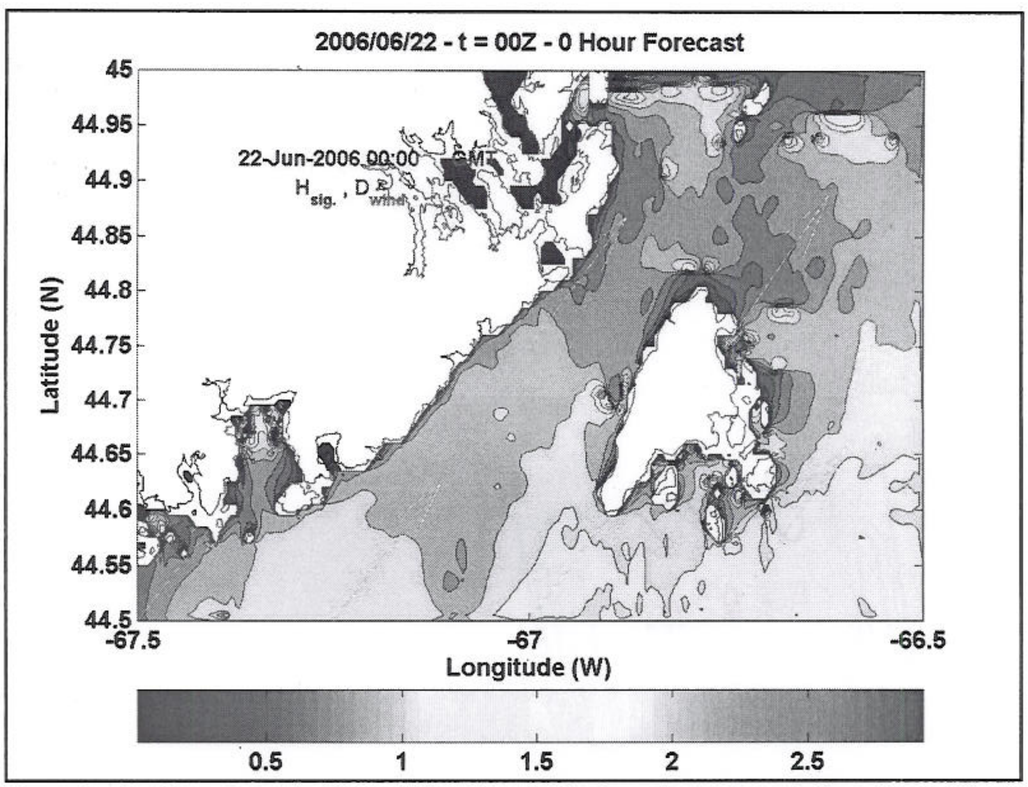


Figure 3: Significant wave height and direction results from the wave modeling efforts.